

Analysis of mine waste by geochemical and geophysical methods (a case study of the mine tailing dump of the Salair ore-processing plant)

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Abstract

Integrated study of the Dyukov Log dump of sulfide-containing mine tailings of the Salair ore-processing plant (SOP) was performed using geophysical and geochemical methods. Geochemical data and results of electromagnetic-frequency sounding and electrical-resistivity tomography were used to establish the geoelectric zoning of the tailings and the relations between the electrical parameters of the environment and the chemical composition of the tailings and pore water. The proposed approach will make it possible in the future to evaluate the amount of tailings. The drainage water flow paths were determined, and the penetration of highly saline industrial solutions into groundwater was proved.

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Introduction

The relevance of the study of sulfide waste is due to environmental risks: acid drainage of toxic elements over tens of kilometers from disposal sites; seepage of highly saline pore fluids into groundwater; pollution of soil and air due to eolian drift of fine-grained material of tailings (Bortnikova et al., 2003, 2006; Lottermoser, 2007; Moore and Ramamoorthy, 1984; Nordstrom, 2015; Salomons, 1995). In addition, interest in the issue of sulfide waste is due to the prospects of extracting valuable minerals from them. High concentrations of Cu, Zn, Ag, and Au, often exceeding their concentrations in existing ore bodies, allow tailing dumps to be considered as industrial waste deposits (Ptitsyn, 2014).

A promising approach to the study of the composition of tailing dumps and migration pathways of drainage solutions is to use geophysical methods. Electrical measurements make it possible to optimize the monitoring of industrial waste deposits by reducing the number of samples taken for geochemical studies, to assess valuable mineral resources, and delineate zones of groundwater drainage flows (Bortnikova et

al., 2011, 2013; Burton and Ball, 2010; Nearing et al., 2013; Olenchenko et al., 2016; Yurkevich et al., 2015, 2017).

The use of geoelectrical measurements to study the composition of industrial waste deposits was first described in a few papers of foreign researchers (Buselli and Lu, 2001; Campbell et al., 1999; Oldenburg and Li, 1999). Since then the construction of geoelectric sections and their qualitative interpretation with identification of electrically conductive zones around areas with highly saline pore water have been studied in sufficient detail. However, there is still no method for reliable differentiation between oxidized and unoxidized zones of water-bearing sulfide tailings and bedrock (Burton and Ball, 2010; Nearing et al., 2013; Oldenburg and Li, 1999). Analysis of geoelectric sections reliably identifies only highly conductive zones due to the salinity of pore water. The nature of the electrical conductivity of sulfide wastes is not completely clear: the contribution of secondary sulfate minerals to the total electrical conductivity has been little studied, except for a few foreign reports (Blowes, 1997; Horton, 2003); scarce studies have been performed to investigate the electrical conductivity of sulfide minerals in the waste body using advanced methods (Nelson and Van Voorhis, 1983; Sheriff et al., 2009). At the same time, geophysical exploration (electromagnetic-frequency sounding, electrical-resistivity tomogra-

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phy) of industrial waste deposits clearly identifies low-conductivity zones containing high concentrations of sulfide minerals (pyrite, arsenopyrite). When the environmental conditions change, e.g., due to groundwater rise and an increase in the amount of precipitation, these bodies become sources of acids and metals (Bortnikova et al., 2011, 2013; Yurkevich et al., 2015).

Understanding the mechanisms of migration and deposition of chemical elements in a waste body and their migration out of the industrial waste deposit requires proper interpretation of electrical data. The latter is based on knowledge of the nature of the electrical conductivity of waste (contributions of the mineral matrix and pore fluid). This allows predicting the transformation of industrial waste deposits based on geophysical data.

The paper presents the results of investigation of the Dyukov Log tailing dump of sulfide-containing mine wastes of the Salair ore field using frequency sounding and electrical-resistivity tomography with verification by classical geochemical analyses. The objective of this study is to establish the relationship between the chemical composition of the waste material at a depth of 2 m and the electrical resistivity of the medium in order to show that local areas with low electrical resistivity (ER) on geoelectric sections are confined to water-bearing horizons with highly saline pore water.

The ultimate objective of the studies is to develop an integrated technique for determining the composition of stockpiled mine wastes and identify the extent of distribution of highly saline water.

Exploration target

The development of polymetallic barite ore deposits of the Salair ore field in the 1930–1980s led to the formation of waste dumps which are still sources of release of chemical elements (Zn, Pb, Cu, Cd, As, Sb, Co, Ni) into the environment. The Dyukov Log tailing dump of the Salair ore-processing plant (SOP) formed as a result of disposal of wastes from the flotation and cyaniding of barite-polymetallic ores bodies in 1942–1975. The tailing dump is located in a natural ravine in the city of Salair (Fig. 1).

The deposits forming the tailing dump came from a natural oxidation zone of ore bodies and therefore consist of highly altered rocks and minerals (Bortnikova et al., 2003). The primary ore minerals are pyrite (3.5%), galena, and sphalerite (0.5% each). Sulfides are on average 30% oxidized. The secondary ore minerals are dominated by iron hydroxides (1%), anglesite, and smithsonite (0.3% each). The main gangue minerals are quartz, barite, and kaolinite. During the existence of the tailing dump, about 1.5 million tons of waste was accumulated in it. At present, the dimensions of the tailing dump are $400 \times 300 \text{ m}^2$; on its surface, there are small ponds which are relics of a hydraulic-mine dump; below the dump along the terrain profile, there is a settling pond receiving filtration runoff from the waste dump (Fig. 1).

Method

Geoelectric parameters. During field work in 2013, $235 \times 235 \text{ m}^2$ areas were delineated on the surface of the tailing dump. Geoelectric sections were measured along three profiles: two parallel profiles spaced 50 m apart and a profile perpendicular to them (Fig. 1). The measurement step along each profile was 5 m, and the length of each profile was 235 m. The measurements were performed using a SKALA-48 multielectrode electrical-survey instrument designed in the Laboratory of Electromagnetic Fields of the Institute of Petroleum Geology and Geophysics (IPGG) of the SB RAS using an electrode array corresponding to the Schlumberger setup. Data processing was performed using the Res2DInv and Res3DInv programs (Loke, 2009). In 2013, the obtained geoelectric data were supplemented with results of frequency sounding using an EMC electromagnetic scanner (developed in the IPGG SB RAS) along six profiles 45 m long (Fig. 1).

Petrophysical characteristics. The moisture content, grain-size distribution, porosity, and density of waste samples were determined by Cand. Tech. Sci. N.A. Golikov in the Laboratory of Experimental Seismology of the IPGG SB RAS.

Physical and chemical characteristics. For geochemical tests of vertical sections, seven pits (3 m deep) were dug and sampled in areas with the lowest electrical resistivity. Physicochemical parameters were determined for water/rock suspensions at a ratio of 1/2 (so-called pastes) under field conditions. This method is well known in the literature (Smart et al., 2002) and gives primary information on the composition of the liquid phase formed upon contact of the waste material with atmospheric water. The electrical conductivity (EC) of the pastes was measured by direct conductometry using a Cond315i instrument (Wissenschaftlich-Technische Werkstätten GmbH). The instrument measures electrical conductivity in the range from 0.0 $\mu\text{S}/\text{cm}$ to 500 mS/cm with a relative error of $\pm 0.5\%$.

The pH and redox potential (Eh) were measured by direct potentiometry using an Ekspert-001 (Ekoniks-Ekspert, Moscow) portable instrument. Before the pH measurements, the instrument was calibrated using standard solutions with known pH values (3.56; 4.01; 6.86; 9.18). The measurement accuracy was $\pm 0.01 \text{ pH}$.

Chemical composition of the waste material and aqueous extracts. Under laboratory conditions, the elemental composition of waste samples was determined by Synchrotron Radiation X-ray Fluorescence (SR-XRF) analysis (Baryshev et al., 1986) at the VEPP-3 storage ring (Budker Institute of Nuclear Physics, SB RAS). Aqueous extracts with a water/rock ratio of 10/1 were prepared, and their physicochemical parameters (pH, Eh, electrical conductivity) were determined by the same instruments as were used in field work.

The Cl^- content in solutions was determined by direct potentiometry using an Ekspert 001-3.0.4 (Ekoniks-Ekspert) portable instrument and an ion-selective electrode. In the concentration range of 10–500 mg/L , the relative error was

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